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Authors:
P.-N. Seo[a], J.D. Bowman[a], M. Gericke[a], G. Greene[b], J. Long[a], G.S. Mitchell[a], S.I. Penttila[a], and W.S. Wilburn[a]

Affiliation:
[a]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b]University of Tennessee, Knoxville, TN 37996, USA/Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Correspondence to be sent to: Pil-Neyo Seo, Los Alamos National Laboratory, P.O. Box 1663, MS H803, Los Alamos, NM 87545, USA

E-mail address: pilneyo@lanl.gov

Phone number: +1-505-665-2766
Fax number: +1-505-665-4121

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A measurement of the flight path 12 cold H_2 moderator brightness at LANSCE

P.-N. Seo[a], J.D. Bowman[a], M. Gericke[a], G. Greene[b], J. Long[a], G.S. Mitchell[a], S.I. Penttila[a], and W.S. Wilburn[a]

[a]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[b]*University of Tennessee, Knoxville, TN 37996, USA/Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

ABSTRACT

We have measured the brightness of the Flight Path 12 upstream/back-scattering partially-coupled cold hydrogen moderator at LANSCE. This measurement was performed in the neutron energy range of 0.8-76.9 meV by using a time-of-flight technique in conjunction with a two-pinhole collimator system. Cold neutrons were observed with a redundant ^{6}Li-loaded glass scintillation detector having an efficiency of close to unity. The detector viewed an area of 0.93 cm^2 on the center of the 12×12 cm moderator surface. A maximum brightness of 1.25×10^8 neutrons·s^{-1}·sr^{-1}·cm^{-2}·meV^{-1}·μA^{-1} was measured at 3.3-meV neutron energy. Statistical and systematic errors of the measurement are 3% and 7%, respectively. The measured brightness is compared to the result of a model calculation and there is a significant disagreement, by a factor of 1.5 at the peak. The performance of the *m*=3 supermirror neutron guide system on Flight Path 12 was also studied with the two pinhole-detector system.

Key words: Moderator, cold neutron, brightness, time-of-flight, two-pinhole system, ^{6}Li glass scintillation detector

PACS: 11.30.Er, 28.41.Pa, 29.30.Hs, 29.40.Mc

1. INTRODUCTION

A new cold neutron beam line, Flight Path 12 (FP12), is under construction at the Manuel Lujan Jr. Neutron Scattering Center at Los Alamos Neutron Science Center (LANSCE). It is dedicated to fundamental nuclear-physics experiments. The first experiment to use this beam line will be a measurement of the parity-violating directional gamma-ray asymmetry in the reaction $\vec{n}+p \rightarrow d+\gamma$ (FP12). This asymmetry is expected to be very small, 5×10^{-8}, and a goal is to measure it with 10% statistical uncertainty [1,2]. The statistical limit of the asymmetry at LANSCE will be determined by the cold neutron flux. In a spallation neutron source the neutron flux depends upon a number of parameters such as the proton current, energy incident on the spallation target, the moderator performance (brightness), and the neutron guide performance. In this paper, we report on a measurement of the brightness of the moderator viewed by FP12 and the performance of the installed neutron guide.

From the engineering design point of view, there are a few decisive parameters that affect upon neutron beam intensity in spallation neutron source such as geometrical parameters, the target-moderator coupling scheme and the ortho-para hydrogen ratio. Kiyanagi *et al*. have shown that in both mock-up experiment and simulation the flux-trap geometry for the target-moderator coupling increased neutron beam intensity compared with other configurations [3]. Earlier experiments with polyethylene moderators to study the dependence of the neutron intensity on the position of the moderator for various types of moderator configurations show that for all moderators the back-scattering geometry is superior to the transmission geometry [4]. The brightness of the cold hydrogen moderator is also sensitive to the ortho/para-hydrogen ratio due to the large difference in total scattering cross sections between ortho/para-hydrogen in the energy region below about 50 meV [5]. Studies on decoupled- and coupled-H_2 moderators show that ortho-para ratio changes significantly the beam intensity [6].

The FP12 views the new upstream/back-scattering moderator in the flux-trap geometry at LANSCE. This unique moderator is a partially-coupled cold H_2 moderator operated in a supercritical state [7]. The geometry of this FP12 target-moderator system is illustrated in Refs. [7,8]. The spatial orientation of the moderator surface is perpendicular to the FP12 beam direction. During the brightness experiment, the ortho-para ratio of hydrogen in the moderator was estimated to be 23/77 [9], which was inferred from comparison between calculated and measured neutron spectra as a function of time since condensing hydrogen and calculated neutron spectra as a function of the ortho/para-hydrogen ratio. The performance of this moderator has not been experimentally studied but has been extensively modeled [8]. Understanding of the FP12 moderator brightness is very important for the NPDGamma experiment because it gives the statistical limit that the experiment can achieve. A measurement will also verify models used to calculate the moderator brightness of a spallation neutron source. The apparatus for the moderator brightness measurement was also used to check the alignment and reflectivity of the newly installed neutron guide system and its performance.

The moderator brightness is a measure of the neutron phase space density on the moderator surface. Thus, it characterizes the performance of the moderator in a way that is independent of the proton current and the acceptance of subsequent neutron optics and collimation systems. In this paper the brightness is given in units of neutrons$\cdot$s$^{-1}\cdot$sr$^{-1}\cdot$cm$^{-2}\cdot$meV$^{-1}\cdot\mu$A^{-1}.

2. EXPERIMENTAL SETUP

A. LANSCE short-pulse spallation neutron source

The operation of the short-pulse spallation source at LANSCE is described in detail in Ref. [10]. Very briefly, the 625-μs long, 800-MeV H^- pulses from the LANSCE linear accelerator are injected into the LANSCE Proton Storage Ring (PSR). As a part of the injection process, the H^- particles are stripped of electrons to form H^+. In the PSR protons are accumulated and compressed into pulses with a roughly triangular-shaped longitudinal profile, 250 ns wide at the base. The proton pulses are then directed onto a spallation target at the rate of 20 Hz. During the experiment the average proton current was 120 μA.

The LANSCE spallation target consists of two 10-cm diameter tungsten cylinders [7]. The upper cylinder is 7.5 cm long, while the lower cylinder is 27 cm long. The gap between the cylinders is 14 cm and is surrounded by four downstream moderators and reflector systems. Two upstream moderators are located above the upper tungsten cylinder. The FP 12 views a cold H_2 upstream moderator with 12×12 cm surface area and 5-cm thickness.

B. Setup for the brightness measurement

To measure the moderator brightness, neutrons directly from the moderator have to be detected, without seeing neutrons that have been reflected from the neutron guide surface. To measure such direct neutrons, a two-pinhole collimator system was constructed. Two pinholes define the area viewed on the moderator surface as well as the solid angle of the detector. An upstream pinhole collimator defined the magnification of the area viewed on the moderator and the downstream pinhole collimator defined the active detector area. Two sets of collimators were fabricated from materials with large neutron absorption cross section, gadolinium (Gd) and ^{6}Li-loaded plastic. The size of the pinholes was chosen so that the neutron count rate in the detector was not significantly affected by deadtime or pulse pileup. For the guide performance study, the downstream pinhole and detector were mounted on a scanner that could be moved along the x- and y- axes with the z-axis defined as the beam direction.

Figure 1 for the Gd pinhole setup, shows the experimental layout for the moderator brightness measurement (not to scale). The spallation target-moderator system was located in the target crypt, which was surrounded by a 5-m thick biological shield. The 7.93-m long neutron guide system, which started at 1.37 m from the surface of the moderator, had a vacuum housing, which during the experiment was filled with natural helium (He) gas to atmospheric pressure, 580 torr at Los Alamos. The upstream pinhole was located 2.6 m from the end of the guide and the downstream pinhole was 2.6 m behind the upstream pinhole. The total length of the neutron flight path, from the moderator surface to the detector, was 14.5 m.

The target crypt was kept under vacuum (about 0.3 torr) and about 25% of the residual pressure was due to natural He. Neutrons from the moderator entered the neutron guide through a 3.2-mm thick aluminum (Al) window. The FP12 *m*=3 supermirror guide system consists of the in-pile guide, the shutter guide, and the chopper guide. A detailed discussion of the neutron guide is described in Section 4.

As shown in Fig. 1 the neutrons leaving the guide through the exit window of 1-mm thick Al passed through 2.6-m air and were collimated by the upstream Gd pinhole. These pinholes were aligned to ±1 mm accuracy with respect to the nominal center line of the guide. Neutrons passing the upstream pinhole traveled 2.6 m in air and were then shielded by a 2.3-mm thick ^{6}Li-loaded plastic with a 3-mm diameter hole. The purpose of the ^{6}Li plastic shielding was to absorb the neutrons without creating a gamma-ray background. Behind the ^{6}Li shielding was located the downstream Gd pinhole. Both of the Gd pinholes were 0.5-mm thick and 1.95±0.01 mm diameter. The ^{6}Li-loaded plastic shield, the downstream Gd pinhole, and the neutron detector coupled with a photomultiplier (PMT) tube were mounted on a scanner that could be moved along the x and y axes. Neutrons were detected in the ^{6}Li-loaded glass scintillator through the reaction, ^{6}Li(n,α)^{3}H. Each of the reaction product deposits its energy into the scintillator material and the light of scintillator was detected by the PMT. The pulse height is independent of the neutron energy, which is negligible in comparison to the 4.8-MeV energy release in the reaction. The ^{6}Li-loaded glass scintillator was 4 mm in diameter and 2 mm thick (Bicron Type NE905). This detector type has 6.6% of lithium by weight, which was 95% enriched ^{6}Li [11]. The downstream collimator was made smaller than the detector in order to eliminate events for which the reaction products escaped from the sides of the detector.

C. Electronics for neutron counting and proton current determination

At a pulsed spallation source the neutron energy can be measured accurately using the time-of-flight (TOF). For the brightness measurement, the neutron TOF window, Δt, was selected to be less than 5% of the neutron TOF at each energy point in order to make the variation of the brightness over the energy window negligible.

A signal from the PMT was sent to a timing-filter-amplifier and its output fed to a discriminator. Events above the threshold were sent to a coincidence unit where a coincidence was formed between the neutron signal and the TOF window, Δt, in order to select neutron events from the desired neutron energy range. The discriminator pulse width of 800 ns determined the deadtime of the electronics. The peak event rate of 8.9 kHz at 15 meV had a deadtime of 0.7%, which was an insignificant correction relative to other errors in this measurement. The electronics were otherwise assumed to be 100% efficient other than the discriminator deadtime.

To reduce the gamma-ray background, pulse-height discrimination was used. After a scan of the discriminator threshold as shown in Fig. 2, the threshold was set to 250 mV. The pinholes and the discriminator threshold resulted in a neutron count rate of about 4 kHz at 5-meV neutron energy. The gamma-ray background was measured by covering the upstream pinhole with a Gd foil. This foil also produced gamma rays through the Gd(n,xγ) reaction, but because of the small solid angle, this contribution to the gamma-ray background was not significant.

The proton current on the spallation target was monitored by counting a pulse train provided by the LANSCE facility. By using a ^{3}He ion-chamber neutron monitor we verified that the neutron flux was proportional to this proton intensity signal. The facility assigned a 5% scale error to the proton intensity signal [12].

3. DATA ANALYSIS

A. Uncorrected moderator brightness

Two sets of data were taken and analyzed to obtain the brightness. An initial data set was taken using the pinholes made of 2-mm thick ^{6}Li-loaded plastic and the second data set was taken using the pinholes made of 0.5-mm thick Gd foil. The measurement with the Gd pinholes had better statistics. The brightness measurement was done in a neutron energy range from 0.8 meV to 76.9 meV.

The moderator brightness, B, was calculated using the following formula:

$$B = \frac{n}{active\ time(\mathrm{ms/pulse})} \times \frac{\Delta t(\mathrm{ms})}{\Delta E(\mathrm{meV})} \times 20\ \mathrm{pulses/s} \times \frac{1}{proton\ current(\mu\mathrm{A})} \times \frac{1}{\Omega A(\mathrm{cm}^2\mathrm{sr})}.$$

Here n is the normalized and background-subtracted neutron counts. *Active time* is the total time used to count neutrons within the TOF window. The time dispersion for the 14.5-m long flight path is calculated from $\Delta t/\Delta E \equiv t/2E$. The quantity ΩA is the product of Ω, solid angle of the detector from the surface of the moderator, and A, the area on the moderator viewed by the detector.

Both data sets were analyzed as follows. Neutron energy, E (meV), was calculated using the TOF and the 14.5 m length of the flight path. Neutron counts for each energy were normalized with the corresponding proton current and then the background was subtracted. The background contribution was found to be 62% at 0.8 meV and 0.7% at 76.9

meV. The TOF instantaneous neutron rate (n·ms^{-1}·pulse^{-1}) was obtained by dividing the normalized and background-subtracted neutron counts by *active time*. The resulting neutron rates as a function of TOF are shown in Fig. 3 (top). A total TOF spectrum measured with the open pinholes is compared with a background spectrum measured with the upstream pinhole covered with the Gd foil. The center of the peak in the TOF spectrum is at 9 ms, which corresponds to neutron energy of 12 meV. The rate was then multiplied by time dispersion ($\Delta t/\Delta E$) to obtain the rate as a function of neutron energy (n·meV^{-1}·pulse^{-1}). This result in Fig. 3 (bottom) shows that the maximum neutron flux is at about 3.3 meV. The peak represents the Maxwell-Boltzmann distribution of the neutron velocities after the moderation. The flux was corrected for the proton pulse rate of 20 Hz, normalized by the proton beam current of 120 μA, and then averaged over neutrons from the area (A=0.93 cm^2) viewed on the moderator surface through the solid angle of the detector (Ω=1.42×10^{-8}sr).

B. Corrections to brightness

The uncorrected brightness was corrected for the efficiency of the ^{6}Li-loaded glass scintillation detector, for the attenuation of the 4.2-mm thick Al windows in the guide, for the attenuation of natural He gas which was inside the guide, and finally for the attenuation by air between the exit window of the guide and the detector.

The efficiency of the detector was obtained from the product of neutron absorption in the detection material and the collection efficiency. The neutron detection efficiency depends on the n-^{6}Li absorption cross section, σ, in the reaction ^{6}Li(n,α)^{3}H, the

^{6}Li atomic density over a detector volume, *c*, and the thickness of the detector, *t*. The cross section is known to better than 1% accuracy and has the neutron energy dependence σ=149/ (*E*), where *E* is in eV and σ is in barn (10^{-24} cm^2) [13]. The detection efficiency can be written as

$$d = 1 - \mathrm{e}^{-ct\sigma} = 1 - \mathrm{e}^{-\frac{0.464}{\sqrt{E}}},$$

where *E* is in eV, c=0.1557×10^{23}/cm^3, and t=0.2 cm. The detection efficiency varies from 80.4% to 99.99% for neutron energies from 76.9 meV to 0.8 meV. In addition to the detection efficiency, edge effects on collection efficiency were considered. The downstream collimator eliminates losses from the edge of the cylindrical detector, however, when low-energy neutrons are captured near the front or rear detector surfaces, it is possible that one of the reaction products escapes, and the consequently deposited ionization energy will be under the threshold of the pulse height in the discriminator unit. The ranges of alpha and triton particles were 7 μm and 34 μm, respectively. A Monte Carlo simulation showed that 3.8% and 0.6% of 1-meV and 100-meV neutrons respectively were not detected. In the calculation, it was assumed that ^{6}Li atoms were distributed uniformly in the detector material. This edge effect is included in the detector efficiency.

The next correction was the attenuation caused by the 4.2-mm total thickness of Al windows of the neutron guide. The cross section of solid aluminum was approximated by taking half of the total cross section of free aluminum atoms given by ENDF/B-VI [14], in order to include the Bragg scattering of neutrons within energy range of 0.1meV-82 meV.

A correction for solid Al was thus obtained by calculating the neutron transmission for half of total Al thickness. Correction due to the Al windows ranges from 4.3% to 1.8%.

The 7.93-m long section of the neutron guide was filled with natural He gas to atmospheric pressure. The brightness data were corrected for the attenuation of the He gas. Natural He gas is composed primarily of ^{4}He, with a $1.37\text{x}10^{-6}$ fraction of ^{3}He by volume. In spite of the large neutron absorption cross section of ^{3}He at low energy, neutron absorption by ^{3}He was negligible because of the low isotopic fraction. The 7.93 m of ^{4}He scattered 1-5% of the neutrons in the 76.9-0.8-meV energy range.

Between the guide exit window and the detector was 5.2 m of air that also attenuated the beam. Assuming 75% nitrogen and 25% oxygen content, the air absorbed/scattered neutrons by 15-37% and by 2-4%, respectively for 76.9-0.8 meV. The total correction due to the aluminum windows, He gas, and air ranges from 18.6% at 76.9 meV to 44.1% at 0.8 meV.

C. FP12 cold H_2 moderator brightness result

The moderator brightness measurements were done in the neutron energy range of 0.8 meV to 76.9 meV. In Fig. 4, the measured brightness is shown together with a Monte Carlo N Particle (MCNPX) model-calculated brightness. Results of the two measurements are plotted. The solid circles were obtained using pinholes of 1.95-mm diameter and 0.5-mm thick Gd foil and data of this measurement are listed in Table 1. Another measurement with fewer statistics was done using a ^{6}Li-loaded plastic sheet with effective 1.93-mm diameter pinholes in the front of the detector and upstream collimation. The neutron counts were corrected as described above. The error bars on the brightness data were determined by statistical and systematic uncertainties. Statistical error varies from 1.5% at 76.9 meV to 4.6% at 0.8 meV. The largest contribution to the 7% systematic uncertainty came from the 5% uncertainty of the proton beam current. An average neutron delay time to escape the moderator after a moderation process was calculated from the distribution of neutron emission time [15]. This average time is about 400μs for 7-meV cold neutrons. This small time is negligible in a present energy distribution. The uncertainty caused by electronics was also negligible.

The two measurements with different pinhole sizes and materials agree with each other. The measured maximum brightness is 1.25×10^{8} $n\cdot s^{-1}\cdot cm^{-2}\cdot sr^{-1}\cdot meV^{-1}\cdot \mu A^{-1}$ at 3.3 meV. This is a factor of 1.5 smaller than the spatially-averaged value of the most recent calculated brightness [7]. The measured brightness is an average over the area of 0.93 cm^2 at the center of the moderator, whereas the calculated brightness is an average over the entire moderator surface. If we assume that the MCNPX calculation of the spatial variation of the moderator brightness across the moderator surface is correct, the discrepancy between measured and calculated brightness is increased.

The discrepancy can be caused by 1) uncertainties in estimation of the systematic errors in the measurement, 2) inaccuracy of the model of the spallation target-moderator system, 3) the uncertainty of the ortho/para-hydrogen ratio during the measurement, 4) moderator non-uniformity, 4) incompleteness of the modeling code, and 5) incorrect cross sections in MCNPX. Earlier model calculations for the FP12 cold moderator showed that the as-built model gives 20% decrease in neutron flux, compared to the physics model, which has less details [8]. Simulations show that factors such as a target length, a target radius, separation between target halves, moderator thickness, etc. affect the neutron beam intensity [3]. Precise values of the spallation target-moderator system in the model need to be checked. Natanabe in Ref. [6] described the moderator temperature dependence and thus ortho/para ratio change on the neutron intensity. Russina *et al.* studied the variation of brightness with position on the FP12 cold moderator with a position sensitive ^{3}He detector [16]. The image of the moderator taken at 0.8-Å neutrons clearly shows that the top of the moderator has 15% lower in intensity compared to the bottom at the moderator. This might be caused by the inhomogeneous illumination of the moderator by the target in low-energy region. The model of the moderator does not predict this behavior. This discrepancy needs to be investigated and it may give a clue to the origin of the discrepancy in measured and calculated brightness. We investigated the possibility of the incorrect backscattering neutron production cross section of a tungsten spallation target used in the MCNPX code. We established that the measurement of W(p,n) production rate for 800-MeV proton by Amian *et al.* [17] agrees with the calculation with the MCNPX code. In model calculation for the H_2 moderator, a hydrogen scattering kernel [5] has been used. Finally, it has been pointed out that some improvements are necessary especially in the para-hydrogen cross section at lower energies [6]. Further investigation of the discrepancy is under way.

4. STUDY OF THE FP12 NEUTRON GUIDE PERFORMANCE AND ALIGNMENT

A neutron guide is used to transport slow neutrons with small losses over large distances from the neutron source to the detector system. The transmission of a supermirror neutron guide is based on the total reflection of neutrons from the inner walls of the guide. The walls are coated with alternating layers of materials with a large contrast in the optical potential for slow neutrons [18, 19]. The neutronic performance of a guide thus depends on the reflectivity of the coating and the precision of the alignment of the guide pieces. Using the two-pinhole collimator system and the ^{6}Li-loaded glass scintillator described above, the performance of the FP12 guide was measured.

The m=3* supermirror guide system on the FP12 has an inner cross section of 9.5×9.5 cm and is composed of 50-cm long pre-assembled guide sections. These sections were then aligned with high precision during the beam line installation. Reflectivity of each 50-cm long coated guide pieces was measured by the manufacturer with λ=4.27-Å neutrons and reflectivities better than 85% at m=3 were observed [21]. Figure 5 shows a typical plot of the measured reflectivity of a FP12 supermirror guide element using 4.27-Å neutrons as a function of the glancing angle $m=\theta_c/\theta_c(^{nat}\mathrm{Ni})$.

The FP12 guide system was surveyed by moving the downstream pinhole and the detector in the vertical (up-down) and horizontal (left-right) directions with about 2-mm steps. Figure 6 shows a conceptual setup for the guide study and some allowed neutron paths from the moderator to the detector. In the FP12 guide system we could detect either direct neutrons from the moderator or once- or twice-reflected neutrons from the guide surface. For the guide survey, 10-meV neutrons were selected with 200-μs gate width and counted over 400 proton pulses.

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* The maximum (critical) glancing angle at which the total reflection still occurs is given by $\Theta_\chi=m\Theta_\chi(^{nat}\mathrm{Ni})$, where $\Theta_\chi(^{nat}\mathrm{Ni})$ is the critical glancing angle of a natural nickel coating [20]. The effective potential of ^{58}Ni for slow neutrons is about 335 neV. This gives the maximum perpendicular neutron velocity of 7 m/s on the coating for a reflection.

Figure 7 shows the beam profiles resulting from the left-to-right (top figure) and up-to down (bottom figure) detector scans. In general, the shapes of two profiles are same; the maximum neutron counts occurs in the center of the moderator and the widths are about 8 cm. The widths are defined by the locations of the downstream end of the guide. In both profiles, we can separate different regions: 1) between 0~±1 cm from the nominal center are neutrons directly from the moderator with no reflection by the guide, 2) between ±1~±3 cm are neutrons with one reflection by the guide, and 3) between ±3~±4 cm are neutrons with two reflections inside the guide. The small peak at –4.5 cm in the up-down scan is an indication of the misalignment of the guide with respect to the moderator. We conclude that the guide is offset vertically from the center of the moderator by about 1 cm. This apparent vertical misalignment does not seriously affect the performance of the guide. Horizontally the guide seems to be well aligned with the moderator. To improve the resolution of the guide survey, the distance between the upstream collimator has to be increased or the diameter of the upstream collimator has to be decreased. In this measurement the length of the view on the inner surface of the guide was typically less than 50 cm.

A Monte Carlo simulation was performed with the two-pinhole system, with the 1-cm moderator offset vertically, which transported the 10-meV neutrons through the FP12 guide. The results for the beam profiles are shown in Fig. 8. The calculated and measured profiles show same overall shape and the peak near –4 cm in the vertical profile caused by the vertical offset of the guide was reproduced. The simulation confirms our interpretations of the measured beam profiles. The angle at which the measured and simulated spectra in

Fig. 7 and 8 cuts off corresponds to m=3.13 and the fall off of the intensity with the angle corresponds to 85% transmission at m=3.

5. CONCLUSION

We have measured the brightness of the FP12 upstream/back-scattering partially-coupled cold hydrogen moderator at LANSCE. Neutrons were detected with a two-pinhole collimator system and a high efficiency ^{6}Li-loaded glass scintillation detector. The measured brightness has a maximum of 1.25×10^8 $n\cdot s^{-1}\cdot cm^{-2}\cdot sr^{-1}\cdot meV^{-1}\cdot \mu A^{-1}$ at 3.3 meV. Statistical and systematic uncertainties in the measurement are about 3 % and 7 %, respectively. Comparing this to the result of an MCNPX as-built model calculation, the measured value is a factor of 1.5 lower than the prediction of the maximum brightness. The discrepancy between the measured and the calculated brightness is not understood and is under investigation. The performance of the FP12 m=3 supermirror neutron guide was also studied with the two-pinhole system by moving the detector system perpendicular to the beam direction to view the inner surface of the guide. With these scans we could observe zero-, once- and twice-reflected neutrons by the guide. The result of the scans indicated that the guide is centered with respect to the moderator on the horizontal axis and about a 1-cm offset in vertical axis with respect to the nominal center of the moderator. The measured variation of the intensity profile of the beam in portions of the phase space, which samples multiple guide reflections, was in agreement with Monte Carlo calculations.

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Table 1. Measured brightness data of FP12 upstream/back-scattering cold H_2 moderator using Gd collimators.

Table 1. Measured brightness data of FP12 upstream/back-scattering cold H_2 moderator using Gd collimators.

Neutron energy (meV)	Brightness ($n/cm^{-2}sr^{-1}s^{-1}meV^{-1}\mu A^{-1}$)	Uncertainty
76.9	1.839e6	1.318e5
60.9	2.444e6	1.751e5
47.6	3.536e6	2.531e5
36.6	5.128e6	3.669e5
29.3	7.663e6	5.482e5
22.9	1.445e7	1.033e5
17.6	2.828e7	2.008e6
13.9	4.674e7	3.337e6
10.6	6.537e7	4.623e6
8.5	7.589e7	5.366e6
6.6	9.500e7	6.722e6
4.9	1.023e8	7.239e6
4.0	1.157e8	8.194e6
3.3	1.253e8	8.875e6
2.6	1.206e8	8.657e6
2.0	1.090e8	7.862e6
1.2	7.758e7	5.752e6
1.0	6.422e7	4.989e6
0.8	5.700e7	4.770e6

The list of figure captions

Figure 1. The layout of the FP12 beam line and experiment for the moderator brightness measurement (not to scale). Neutrons from the moderator traveled through the neutron guide, which had the entrance/exit aluminum window, 3.2/1.0 mm thick, and was filled with the natural He gas. After the guide the neutrons traveled 2.6 m in air and were collimated by the 1.95-mm diameter upstream pinhole. Collimated neutrons were detected by a ^{6}Li-loaded glass scintillation detector, whose active area was defined by the downstream Gd pinhole placed at 2.6 m away from the upstream pinhole.

Figure 2. The ^{6}Li detector is sensitive to neutrons and gamma rays. To determine the pulse heights of neutrons and gamma rays, the number of counts was measured through the pinholes as a function of the discriminator threshold level (filled circle). Then the gamma-ray contribution was determined by mounting a neutron absorber, a Gd foil, onto the upstream pinhole (open circle). The solid black curve is background-subtracted neutron counts. Throughout the brightness measurement, the discriminator threshold level was set to 250 mV, which eliminated most of the gamma rays while keeping all the neutrons.

Figure 3. The top figure shows a time-of-flight spectrum (solid circles) when the up/downstream pinholes were open and a gamma-ray background spectrum (open circles) when the upstream pinhole was covered by a Gd foil. The bottom plot shows the neutron spectrum as a function of energy.

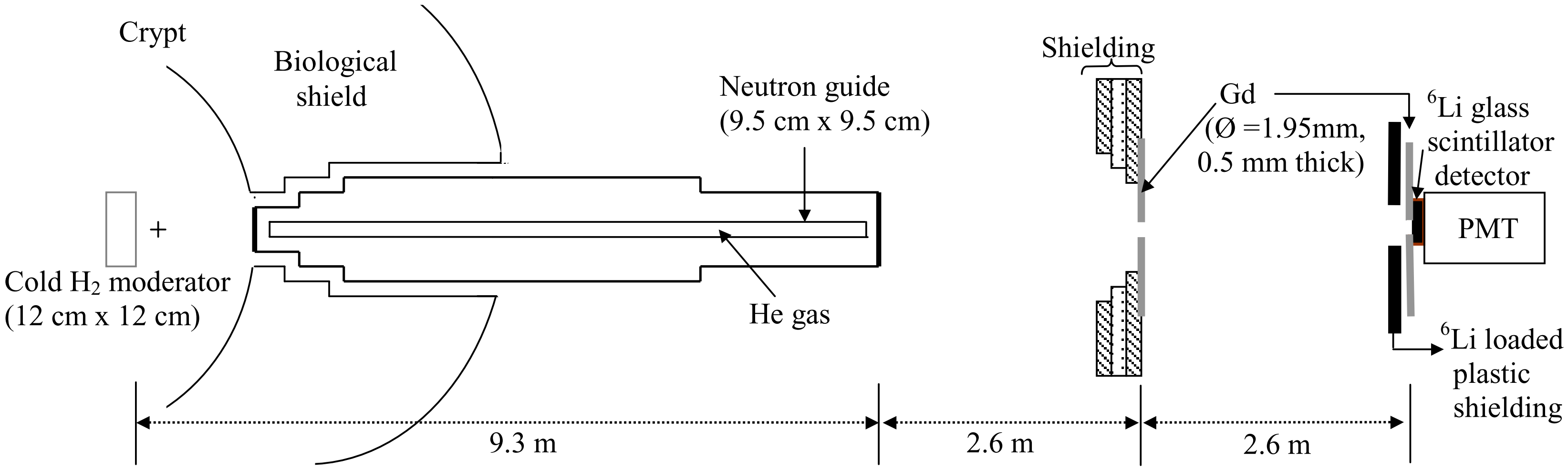
Figure 4. The measured FP12 brightness is compared to a MCNP model calculation. Solid dots show the result of the measurement with the Gd pinholes of 1.95 mm in diameter as the upstream and downstream collimators. The triangles show the result of using the ^{6}Li-loaded plastic pinholes of 1.93 mm in diameter. Measured brightness is averaged over the center area of 0.93 cm^2 on the moderator. The dashed line represents the calculated brightness by Russell *et al*. [7].

Figure 5. A typical plot of the measured reflectivity as a function of the glancing angle $m=\theta_c/\theta_c(^{nat}\mathrm{Ni})$ on the FP12 supermirror guide element using 4.27-Å neutrons.

Figure 6. The setup for the measurement of the phase space dependence of the intensity of the FP12 neutron guide for 10-meV neutrons with the two-pinhole system. Some neutron paths from the moderator to the detector are shown (not to scale). In this guide system neutrons of this energy can have maximum of two reflections.

Figure 7. Scanned neutron beam intensity profile. These are the results from left-right (L/R) and up-down (U/D) detector scans with 10-meV neutrons, 200-μs gate width, and counting over 400 proton pulses per point.

Figure 8. Monte Carlo generated beam profiles in x and y directions for 10-meV neutrons for the experimental setup used in the measurement.



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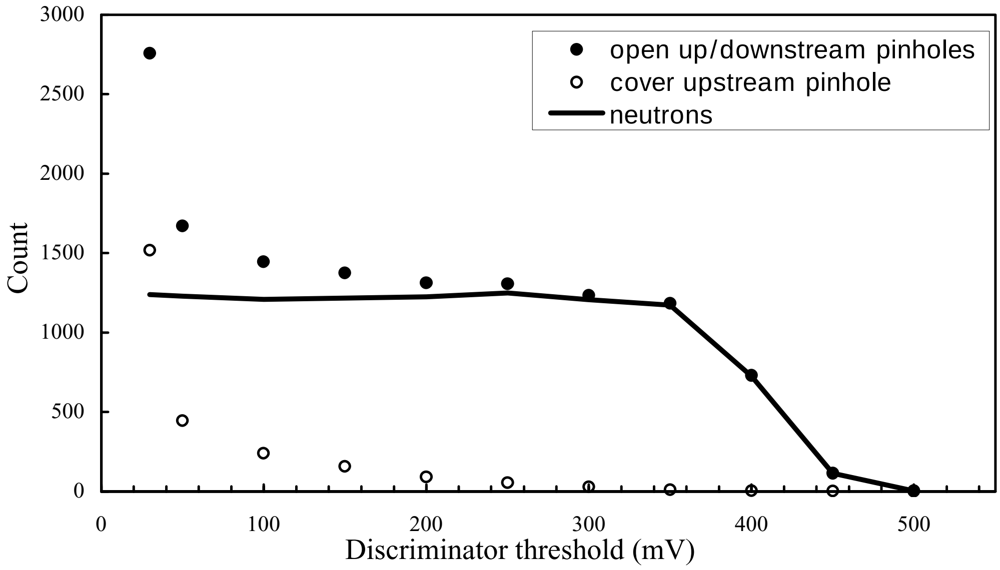

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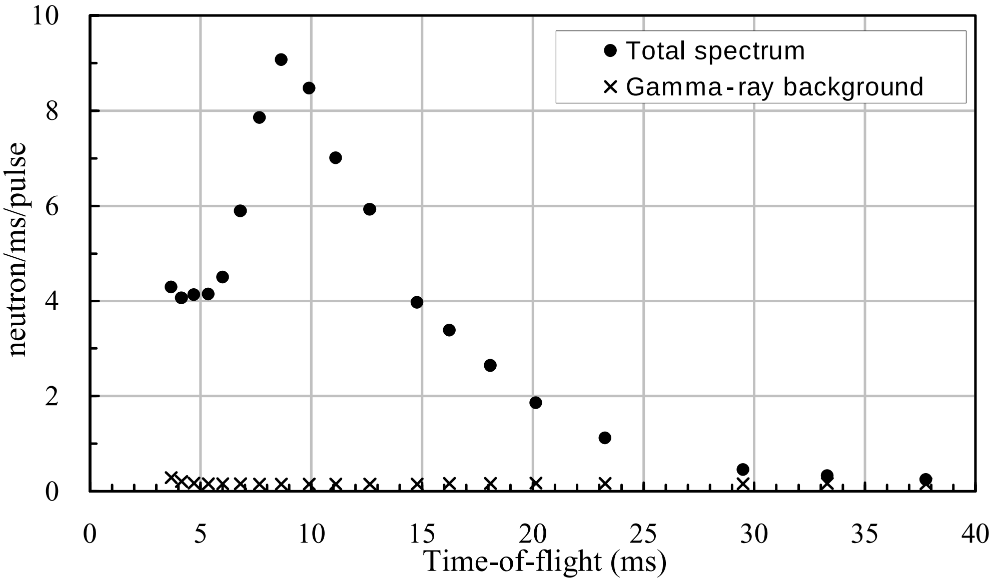

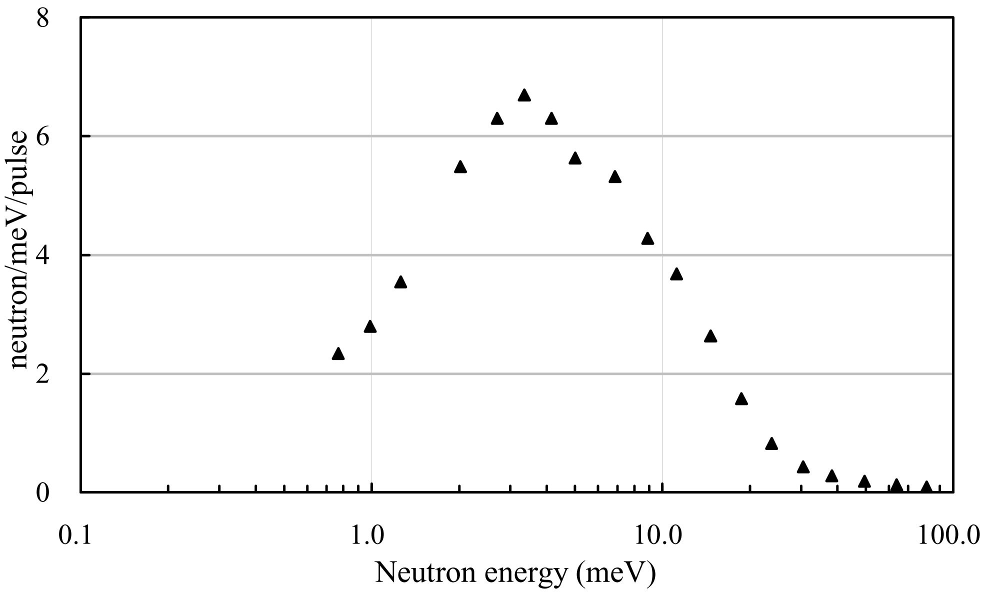

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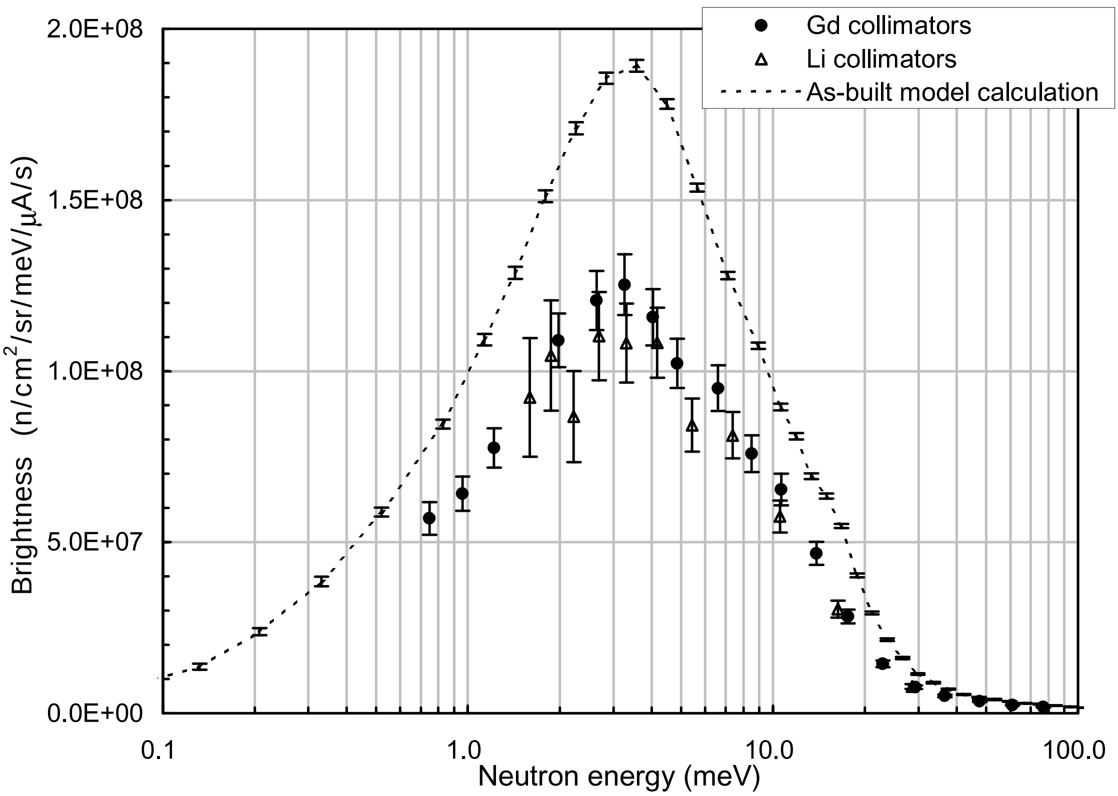

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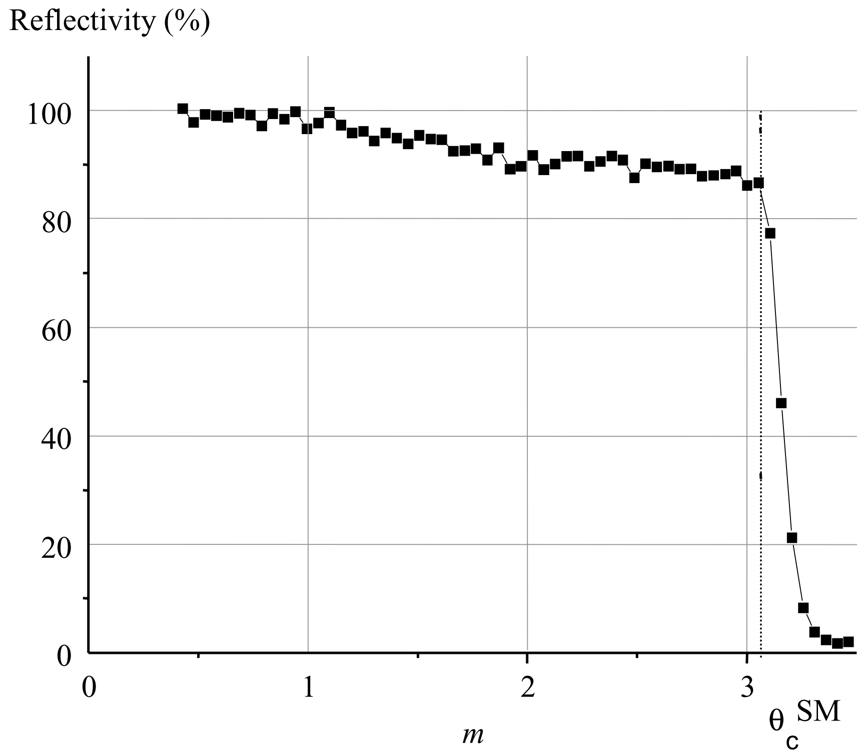

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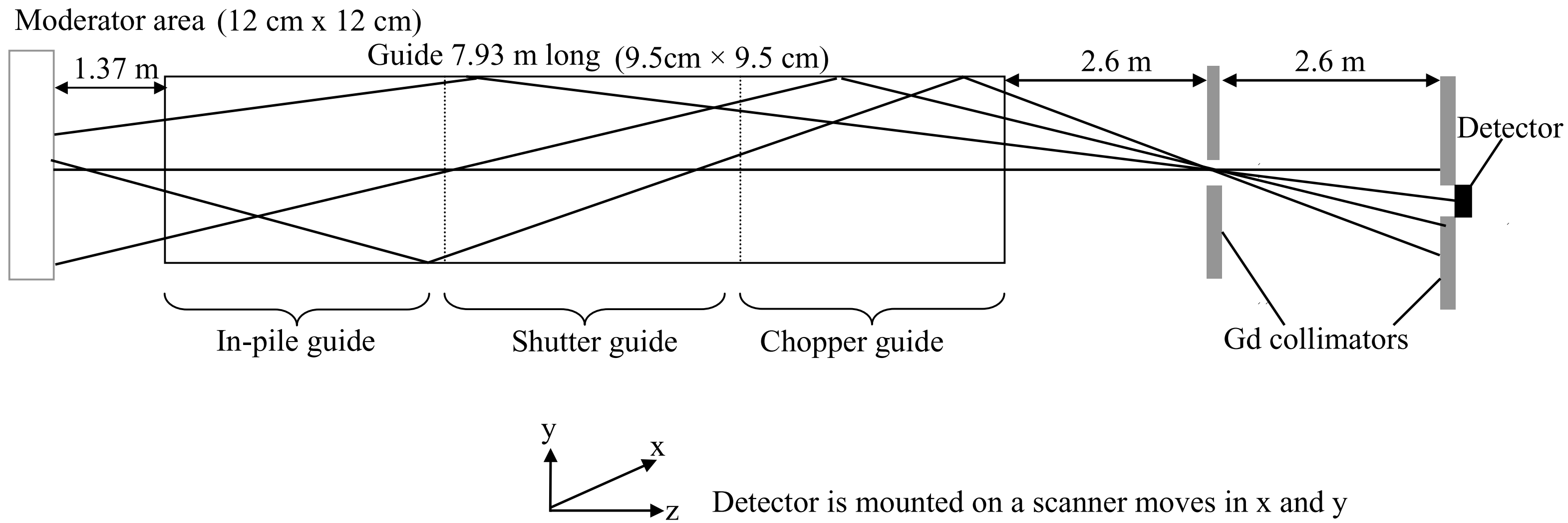

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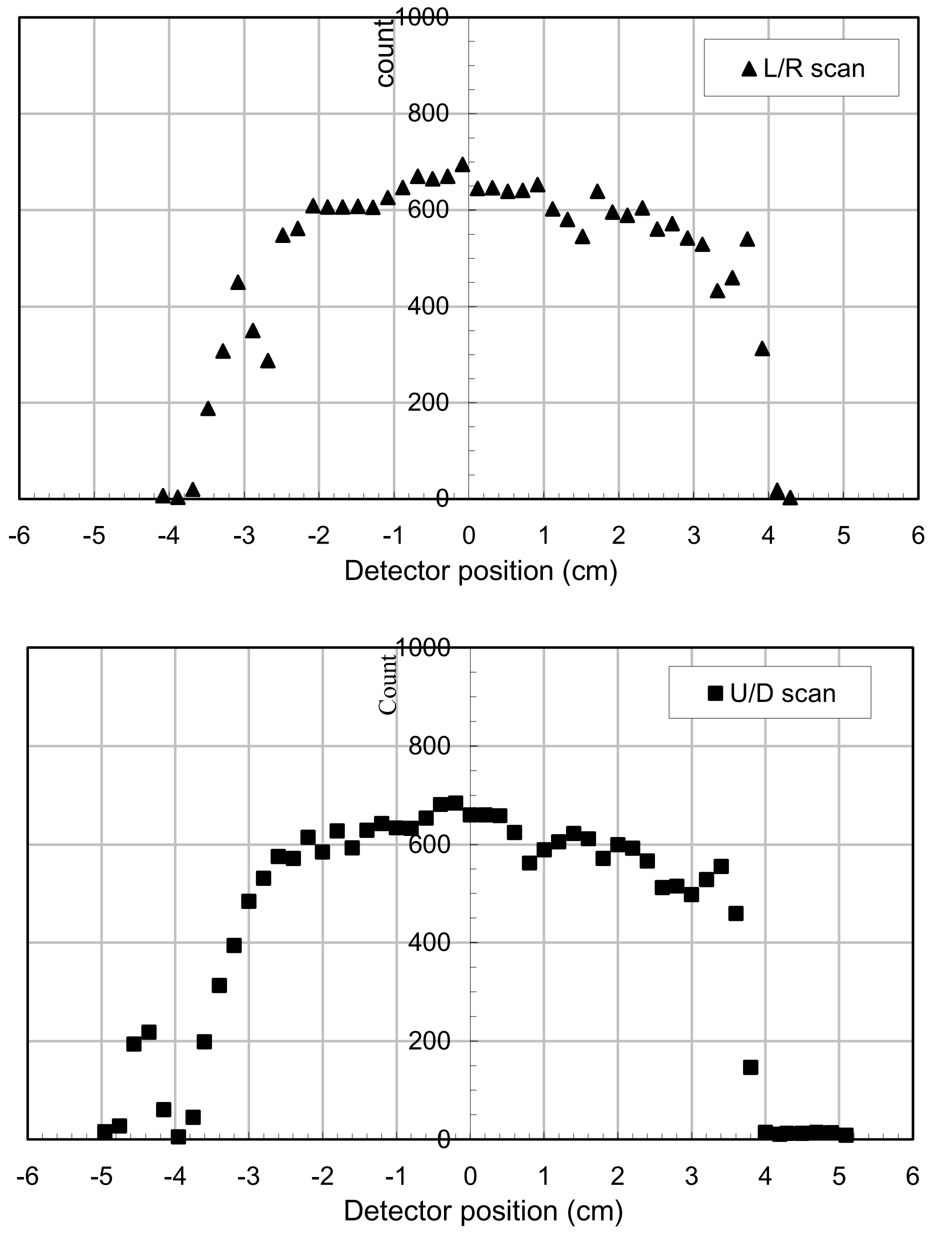

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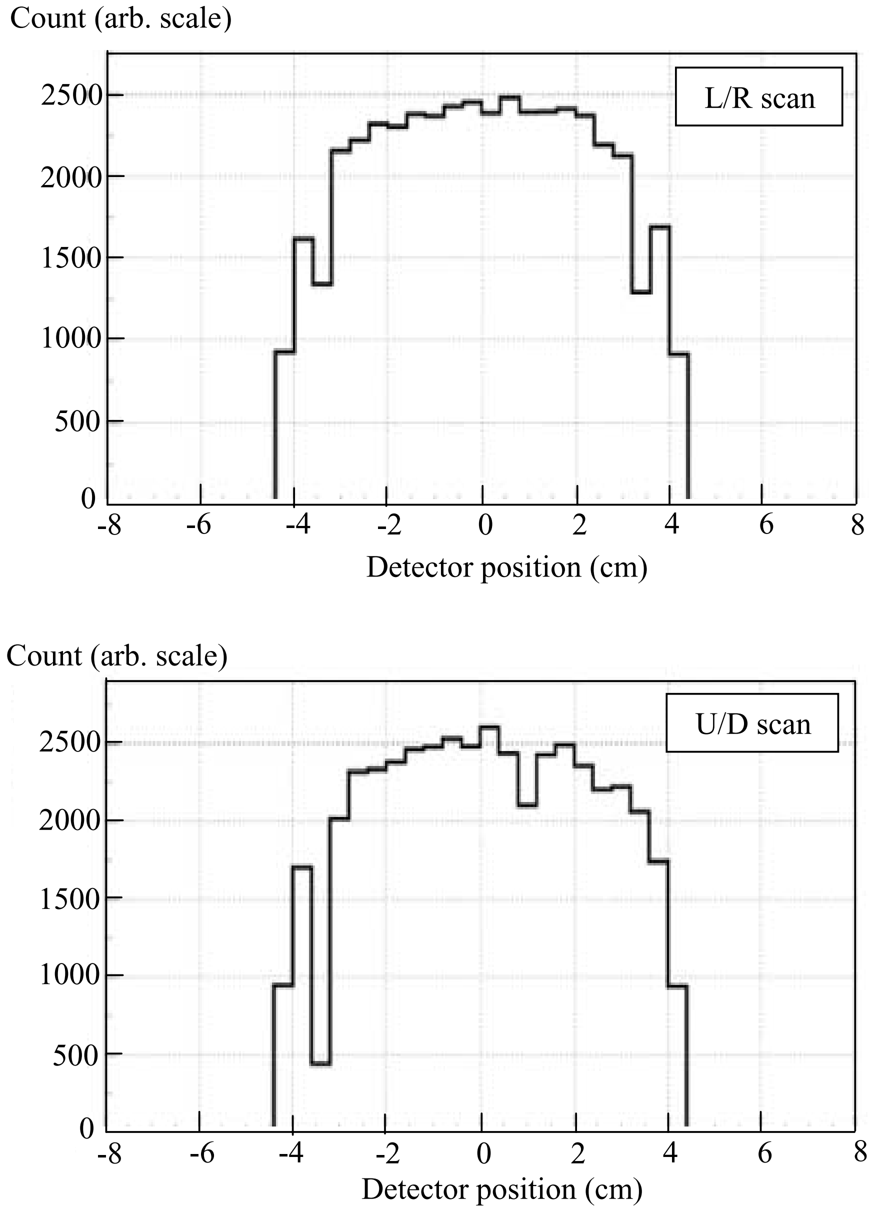

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